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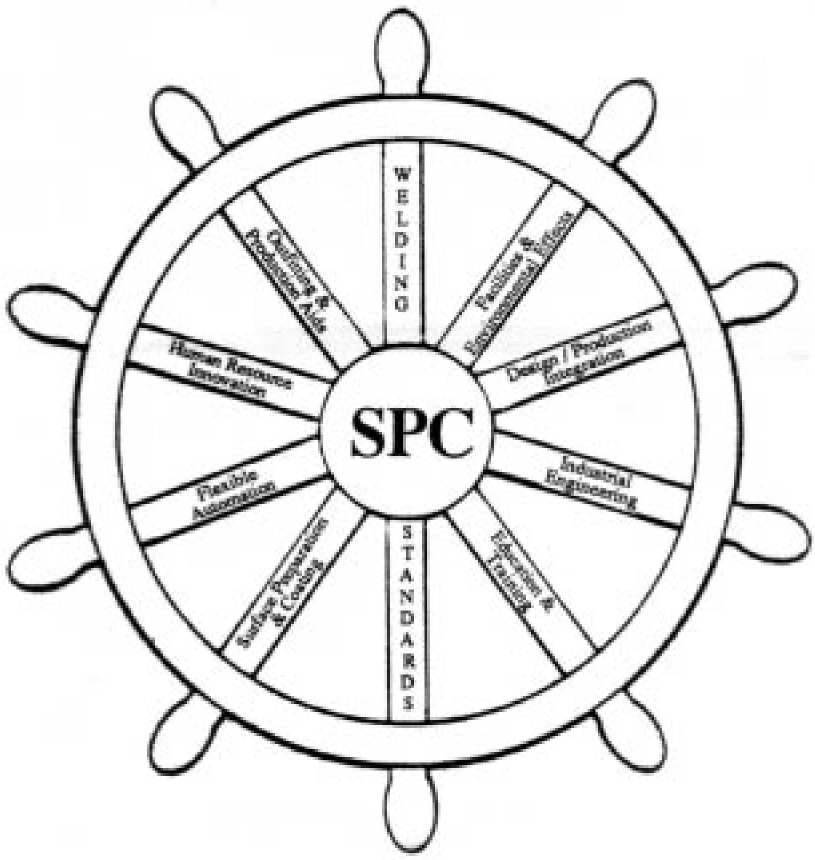

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Advanced Industrial Measurement Systems for Productive Shipbuilding

3A-1

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ABSTRACT

Modern shipbuilders have embraced the concept of modular construction and are realizing the gains in productivity associated with these methods. Further gains in productivity are achieved if these modules are built and erected "neat," that is, without the traditional excess material normally trimmed at erection. Construction of "neat" hull blocks requires rigid control of accuracy throughout the production cycle. Interim products, from fabricated parts to erected hull blocks, must be measured to acceptable tolerances to prevent excessive rework.

The object of this paper is to analyze viable types of advanced measurement techniques supporting the process requirements of "neat" modular construction. Documentation of costs and difficulties associated with each measurement technique selected are also analyzed.

The first part of the paper is a general description and analysis of the systems. The second part describes actual demonstrations of three measurement systems and analyzes them in the shipbuilding environment. Demonstrations of digital theodolites, automated photogrammetry and an optical laser system are described and analyzed.

INTRODUCTION

This paper is a synopsis of an NSRP project "Advanced Measurement Techniques for U.S. Shipbuilding" (1). The object of the project was to classify and analyze as many viable types of industrial measurement systems as possible for use in a shipyard. The following measurement systems were analyzed:

1. Photogrammetry including convergent, stereo, digital image processing, and automated analysis methods;
2. Digitizers, with sonic and infrared systems;
3. Theodolites, including standard manual optical instruments, computer linked systems, and motorized laser targeted systems;
4. Coordinate measuring machines; and
5. Lasers scanners.

The first five groups of systems were the focus of the first part of this paper. The second part of the paper is an on-site analysis of the following specific industrial measurement systems from the general groupings above:

1. Theodolite, with a directly attached and dedicated computer for automated analysis of measurements;
2. Photogrammetry, convergent, with an automated photogrammetric analysis system; and
3. Optical Laser, where bearing and range are obtained from a single point.

SYSTEMS ANALYSES

Table I shows and compares the cost, accuracy, manning requirements, set up time, time required to obtain results, and reliability for each system.

There are four distinctly different photogrammetric systems with possible shipyard applications. These photogrammetric measurement systems are all based on photographic processes, but the two methods by which the photos are taken, and the various methods by which they are analyzed, are significantly different.

	COST [1] ($1,000)	ACCURACY [2] (stated)	MANNING [3] (persons)	SET-UP (hours)	RESULTS [4] (days)
PHOTOGRAMMETRY					
CONVERGENT	100 - 300	1 : 50,000	2 - 6	4	0.5 - 3
STEREO	100 - 300	1 : 20,000	2 - 6	4	0.5 - 3
DIGITAL IMAGE	130 - 200	0.08 mm	2	4	0.2 - 1.5
AUTO ANALYSIS	225 - 275	1 : 200,000	1 - 2	4	0.2 - 1.5
THEODOLITES					
STANDARD MANUAL	5 - 50	0.025 mm	2 - 3	4	1 - 2
COMPUTERLINKED	40 - 100	0.025 mm	2	4	0.5
MOTORIZED, LASER GUIDED	350	0.025 mm	3	8	INSTANT
DIGITIZERS					
SONIC	10-25	0.10 mm	1	0.5	INSTANT
INFRARED	60	0.5 mm	1 - 2	0.1	0.5
LASERS					
THEODOLITES - LASER RANGE	190	1mm	1	4	INSTANT
SCANNERS	150	@1mm	1	4	INSTANT
COORDINATE MEASURE MACHINE	5-300	.025 - .0025mm	1	4	INSTANT - 1

1 A rough approximation of initial system cost. Costs vary significantly because of configurations available in the various instruments. A range of costs indicates a range for the cost of a typical, basic system to one with standard additional features.

2 Accuracy is stated in two different ways. An accuracy written as 1:50,000 is typical for a non contact type of measurement device such as photogrammetry, where the camera can be set at various distances from the object. For example, if the field of view is 20 feet across, a 1:50,000 accuracy will be 20/50,000, .0004 feet or .005 inches. The other method of accuracy description is a dimension directly on the object, such as .01 inch. An accuracy of 1/32 inch was considered acceptable for a shipbuilding measurement device.

3 Manning requirements am included as a range. Most all the systems could conceivably be operated by a single skilled person. The most efficient number of operators and assistants could range from 2 to 6, depending on the system and the turn-around time desired.

4 Time required to obtain results is a range dependent on the difficulty of the job and the number of points to be measured.

TABLEI

SUMMARY COMPARISON OF SYSTEMS

Convergent Photogrammetry

The convergent method is one of two methods of photogrammetric measurement. Camera stations are arranged such that camera axes are inclined, or meet at an angle, relative to a. normal view of the object and converge toward one another. Discrete points on the object must be easily identified in the photos or physically targeted, usually the latter. The positions of the various points of interest are determined by a complex mathematical 3-D triangulation network.

Typical photogrammetric measurement equipment consists of a terrestrial camera, flash units, photo development lab, analytic compiler, and a computer with customized software.

Known camera positions are required to perform the photogrammetric measurements. Some operators pre-survey camera locations relative to the measured object with theodolites. Some systems have simulation software to predict the best camera locations. Sophisticated programming of the triangulation schemes with a few pre-measured control points on the object allow determination of camera locations solely from analysis of the photos in the compiler.

Discrete points of interest must be manually targeted, usually with an adhesive backed bull's-eye. Camera placement should be carefully planned, possibly with the use of models, to eliminate delays at the sight or rework for lack of coverage. The effect of surroundings on locations and lines of sight should also be evaluated. The only required externally measured data are a few distances between pairs of points on or near the object which serve to establish scale.

Analysis of photographs is done on a photogrammetric analytic compiler, a machine for manually viewing and digitizing the photographs into numeric information for synthesis by computer. Each point of interest must be identified and targeted individually by the operator for entry into the computer file. The machine accurately records the two dimensional position of all visible points of interest in one photo at a time. The two dimensional positions from the various photos are combined in a complex triangulation network to fix the points in three dimensional space.

A key element in the analysis is rigorous analytical formulation of the mathematics involved and subsequent programming of the same to develop the analytical software. Processing by a computer can produce a variety of accurately scaled products such as tables of offsets, one-line diagrams and drawings.

Targeting of control points and otherwise difficult to identify points, such as flat surfaces, is required. Adequate lighting must be provided. Results are usually available one to three days after photography occurs, depending on the complexity the of structure, proficiency of the analytical machine operator, sophistication of the software analysis package and the capability of the computer.

Stereo Photogrammetry

The other standard method of photogrammetric measurement is the stereo method. Usually, two cameras are used at the same time to take two overlapping photographs called a stereo pair. Camera stations are arranged with roughly (± 10 degrees) parallel axes to the target and arranged to completely cover the subject with overlapping photographs. Relatively simple but complete manual digitizing of photographs is performed by a special photogrammetric analytic stereocompiler, then processed by a computer to produce a variety of accurately scaled products such as tables of offsets, one-line diagrams, and drawings.

The key difference between the convergent and stereo methods of photogrammetry is that the stereo photos are taken at nearly right angles to the object whereas the convergent photos are at various angles. Subjects of stereo photogrammetry need not be targeted, but discrete points of interest may be targeted. This feature is desirable when large areas must be surveyed and targeting would consume a large part of on site time.

The angle at which photos can physically be taken, dependent on access to the subject or other obstructions, is another factor to consider in selecting stereo or convergent methods. The inability to photograph an object at nearly right angles may prohibit the use of the stereo method. Accuracy of stereo photogrammetry is less than half that of the convergent method.

Camera stations should be located 15 - 30 feet from the object being measured. This distance can be reduced by the use of special cameras, or increased at the expense of less accuracy. Targeting of control points is required. Lighting may be required for poor light situations. Photographic analysis is done off site in an office environment. The imposition upon regular shipyard operations is no more than for convergent photogrammetry.

Digital Image Photogrammetry

Digital imagery is a refinement in the method of photogrammetric analysis. Photographic methods and triangulation techniques are basically the same as other forms of photogrammetry. Discrete points are located by the photo analyzer operator, then the computer creates a digital file for that point on that photo. The same points on related (roughly 60% overlapping) photos are similarly located, but measured automatically using digital correlation techniques and stored as digital image patches. Patches are distinct groupings of individual pixels (various shades of dots in the digitally stored picture) which define a particular point and its surroundings. These patches have smaller digital image files to keep computer storage space requirements low, but still include enough of the image for subsequent correlation.

The core of the system is the Digital Comparator Correlator System (DCCS) (2) which performs automatic point correlation analysis on about 80% of the points. This reduces operator involvement and fatigue significantly. In addition, the DCCS uses a post-process operation, called least squares correlation, which redigests all the correlation information to refine the final measurement.

However, the existing system, which uses convergent photos, has not been tried on a purely industrial application. A new system under development uses similar digital imaging but is designed to use stereo photos on a special analysis system and stereo pair viewing screen.

Site preparation, and imposition on regular shipyard work would be similar to that for the other photogrammetric methods. The operator identifies control points and other points of interest on the master photo; i.e., the first photo on which that point appears.

Points on the master photo are identified by the operator on subsequent photos, then automatically correlated to the master photos (by the digital image processing software) to perform the triangulation required for precise measurement. Once the integrated software performs the triangulation work, each point measured is identified as a set of x,y,z object coordinates.

Automated Analysis Photogrammetry

The only system in this category is the STARS (Simultaneous Triangulation and Resection System) (3). The method of photography is very similar to standard convergent photogrammetry. Therefore,. this description will dwell mainly on the specifics of STARS.

The key to STARS is the Autoset-l automatic monocomparator. The photographs are shot with use of retroreflective targets which must be manually placed on the object. A powerful strobe flash on the camera illuminates the targets which then show up as easily identified bright spots on the photographs. Once each overlapping photograph in the set that cover the object have been manually calibrated into the system, the Autoset-l automatically sights and analyzes each of these bright targets.

The system turns the collection of points from the photographs into digitized information. The software package then performs the triangulation analysis to measure the object. This information can be put into a form readily usable by another system, or produce offset tables in the measured object's coordinate system.

The main advantage of STARS is that the operator of the monocomparator is spared the arduous task of manually and visually identifying each point to the system. The operator simply identifies a few control points to marry one overlapping convergent photograph to the next then lets STARS collect all the other points.

Sonic Digitizer

Sonic Digitizing is a method of 3-D position indicating that works on the principal of analyzing the time for a sound generated at the point of measurement to travel to a grid of calibrated microphones (4). A spark emitting probe is manually positioned (or attached in the case of motion analysis) at the point on the object to be digitized. A spark is generated at the end of the probe. A precisely placed system of four microphones, mounted on a rack lying in a single plane, each senses the distance to the probe by timing the signal. The timed signal is processed to a digitized electrical signal and recorded in a file, on the host computer. Post-processing of the raw signal establishes a data file of coordinates based on the measured object's coordinate system.

The volume of optimum measurement is limited with this device to a 12 foot cube. Measurement within a 25 foot cube is possible with some loss of accuracy. The item to be digitized must be accessible to the operator to point the entire surface with the emitter probe. Up to 16 probes can be accommodated by one device, but for an industrial measurement project not involving dynamics, too many probes would be overkill.

A number of operators can work one system simultaneously using probes emitting different frequencies to measure different parts of an object at the same time. Conversely, one operator can use one probe set at different frequencies to identify different parts of the same object. For example, one frequency can be used for plating, one for stiffeners, and another for pipe. The different frequencies show up on the graphics display as different colors or coded by different symbols.

Each point on the measured item must be in a clear line of sight of at least three of the microphones. Areas much larger than the limit for required accuracy can be done piecewise by moving the object or microphone array to provide overlapping coverage. Welding in the immediate vicinity is likely to interfere with the system. Extreme air movement in the area must be limited.

A multiplexer unit converts the sound data to ASCII format for processing by computer. The basic software included with the system catalogues output and performs simple spatial calculations to give an x,y,z data file. The data can be presented in various two dimensional views of the three dimensional objects.

Infrared Digitizer

The infrared digitizer is similar in principal to the sonic digitizer in that a signal generated at the point to be measured is received by a device, set in a predetermined reference frame, to determine the position of the object. The only system known to fall in this group is called OPTOTRAK (5).

The OPTOTRAK measurement system consists of up to 256 light emitting diodes as markers either attached to or made to contact the object at points to be measured. As the marker is activated it is sensed by at least 2 but up to 24 dual axis infrared position sensors, or cameras, which determine a line of sight to the marker. Sets of two dimensional coordinates are analyzed to give a three dimensional position for each of the markers. The system was developed primarily

for motion analysis but is adaptable to industrial measurement. It is presently limited to a 5m (16 ft) radius from the camera to the marker, but is adaptable to larger scale projects without motion.

The system requires 120V power and must be isolated from other infrared light sources. Maximum cabling distances have the controller unit 30m (100 ft) from the cameras and the host computer 45m (150 ft) from the controller. The object must either be pre-targeted with wired emitters or accessible to a technician to direct a probe to the object for contact measurement.

Standard Manual Theodolites

Theodolite industrial measurement systems are logical adaptations of standard land surveying instruments. These optical instruments measure horizontal and vertical angles and are usually operated in pairs for industrial measurement. When a line of sight from two instruments intersects on a point on the object being measured, the point is fixed in space. The horizontal and vertical angles associated with each point are then converted to 3 dimensional coordinates through 3 dimensional triangulation algorithms.

The best modem systems for industrial measurement employ electronic theodolites tied into a computer with software to quickly compute the positions the instant both "guns" are set on the target.

The operator(s) must have reasonable line of sight access to the target along most of the surface being measured. Theodolites can be moved and reset to cover different parts of a difficult to cover target, but such a procedure increases measurement time and complications. Items are usually targeted so that both theodolites are positively aimed at the same point. Movement of heavy machinery near some measurement sites can upset theodolite calibration and should be minimized.

The basic, manual adaptation of the land surveying theodolite measuring is a manual theodolite. Manual instruments sight on cross-hairs through a magnifying telescope to measure horizontal and vertical angles. They are usually mounted on a tripod and a tribrach for leveling. Simple instruments have external micrometer type scales and, even if of high quality, are limited in their accuracy. Better instruments have lighted, enclosed and magnified optical micrometer scales which can be more accurate, the best of which virtually eliminate human error in reading the scales. The best and most accurate machines have electronic digital readouts which make reading much easier and less error prone.

The difficulty of processing data can range from tedious and time consuming to very simple, depending on how advanced the system is. A very simple system will require hand recording of measured angles and manually calculated basic trigonometry to determine 3-D positions. Data should be reduced by computer using readily available software that includes error analysis of the theodolites being used. Good software can usually arrange the output in a form directly useable by a shipyard's main computer. The biggest problem with a manual system is visually reading the theodolite scale and either writing the readings for later analysis or verbally calling the readings to a third person who records them in writing, and then enters them into the computer or manual calculation routine, a tedious and error prone system.

The measurement site should be isolated from heavy machinery movements. The object is usually targeted for easier point recognition. Lighting may be needed if the measurements are taken at night to avoid other work, normal passage of heavy machinery, or intense sunlight. For efficient measurement, reasonable access to the object must be provided.

Computer Linked Theodolites

An advanced theodolite system is one that is directly linked to a computer for instant and automatic analysis. Although such systems are still manually sighted, they use electronic theodolites that send the measured angles to a dedicated host computer for instant analysis. Systems that fall into this group are the

1. AIMS II (Analytical Industrial Measuring System) (6;
2. CAT 2000 (Coordinate Analyzing Theodolite) (7); and the
3. ECDS 2 (Electronic Coordinate Determination System) (7).

The key differences between the basic and the advanced theodolite systems is the direct link to a computer. Thus the possible human errors in optical scale reading and in data recording of a manual system are avoided. This also means that the data are fed directly to a system designed specifically for the industrial measuring task so that results are instantaneous once the system is established in the object's coordinate system.

The systems are available with laser beam generators for targeting. This arrangement insures that both instruments are focused on the same object and eliminates the need to manually target the object with proper light conditions.

Computer software designed specifically for these systems speeds the process of setting up the instruments, corrects measurements for instrument misalignment, has special routines to protect against power loss and incorrect readings, and many other advantages of a purpose built system.

The only difference for planning purposes is that a power source must be provided to the computer. The theodolites alone can be run on batteries but the standard host computer needs power. An adaptation of the system, although limited in on-site data information capacity, uses a portable computer.

Motorized. Laser Targeted Theodolite

An advanced theodolite system is AUTOCAT (6), short for AUTOmated Coordinate Analyzing Theodolite. The AUTOCAT measurement system consists of at least two digital cameras mounted in electronic, motorized theodolites and directly linked to the host computer. A third electronic, motorized theodolite is a laser beam generator used for targeting and providing a third reference line. The system can be computer driven based on the table of offsets from the object, or operated by a joystick based on the live images from the digital cameras.

In either mode, the laser is directed at the point to be measured. The two digital cameras are also directed to the general position of the laser spot and a digital image of the laser spot is analyzed for its position relative to the true axis of the reading theodolites. The analysis fixes the position of 'the point in space.

The laser theodolite can be used as a third reference line but tends to make the system less accurate. The laser spot is actually a revolving circle of light if seen at a right angle to a surface. At any other angle it appears as a revolving ellipse. The analysis of the image from the digital cameras can compute the centroid of the ellipse and give a better line of position than the pointing of the laser alone.

An additional planning requirement is that the analysis of the laser dot requires somewhat controlled light conditions. The demonstration of this system was inhibited by bright sunlight making, the laser dot barely visible to the digital cameras and at some angles blinding the cameras. These drawbacks negated the field test of AUTOCAT.

Operational advantages are similar to that for the STARS photogrammetry system in that operator fatigue is greatly reduced so that measurements can be made more reliably and quickly. However, the on-site hardware of the system is heavy and bulky, with a fair number of cables, making it less than portable.

Laser Ranged Optical Theodolite

A relatively new system called ACMBTER (Accuracy Control METER) fills this category. ACMETER (8) works on the principal of obtaining a bearing and range from a known location to fix a position in space. This is similar to getting a bearing and range from a radar for navigation.

ACMETER obtains the horizontal and vertical bearings with a single, optical theodolite. Built into this same instrument is a range finding laser. The two work together to give a fairly accurate bearing and range to a point on the object.

The integrated system contains the ACMETER, a directly attached computer-like black box, laser reflective targets, and software to digest all the triangulation. All points of interest must be targeted, not only to make positive identification, but to provide the laser with a good reflective surface to get accurate distance readings.

Coordinate Measuring Machines

Coordinate Measuring Machines (CMM) are mechanical contact devices with mechanically actuated x,y, and z axes for accurately measuring 3-D items. They are usually used for precise measurements of machined surfaces of relatively small parts. The largest machine surveyed could measure a part 2m x 11m x 3m (6ft x 33ft x 10ft) (x,y,z). The best machines are relatively slow but extremely accurate and sensitive. As such, they are not ideally suited to the shipyard environment of dust, vibration and less stringent accuracy requirements. Some manufacturers will "downgrade customize" their machines to the desired accuracy and the environmental conditions encountered, but other types of measurement systems are more appropriate.

Laser Scanner

The only known laser scanner type system is the tracking system designated the LTS-310 (6). The LTS-310 was developed as a very accurate device for measuring moving objects. A special laser reflector is attached to the object at the point to be measured, then the system casts a scattered laser beam in the general direction of the reflector and detects the reflection to determine its position in space. The system was not developed for stationary industrial measurement, but should be adaptable.

System planning requirements seem to be as simple as targeting the object and fixing the position of the LTS-310 relative to the object before starting. The system is still under development.

FIELD TESTS

This section is an account of field tests of the three specific industrial measurement systems that were made available by the manufacturers. The testing was performed under somewhat realistic conditions at NASSCO. The following systems were evaluated:

1. Theodolite, with a directly attached and dedicated computer for automated analysis of measurements;

2. Photogrammetry, convergent, with an automated photogrammetric analysis system; and

3. Optical Laser, where bearing and range are obtained from a single point.

A laser targeted automated theodolite system was also tested, but the bright sunlight made the laser unreadable by the cameras. The system needs further development before use in most shipyards.

General planning for all of the field tests consisted of:

1. Determining which block was to be measured;
2. Identifying discrete points of interest to be measured;
3. Determining the type of coordinate system to be used (local or object);
4. Identifying control points and construction of a control file;
5. Placing the instrument(s) at the job site;
6. Orienting the coordinate system axes;
7. Checking for sight line interferences and space limitations; and
8. Determining any system specific operating restrictions.

All the systems tested required placement of targets on the object. Differences in the types of targets are significant. Discrete points of interest to be measured were chosen because they represent two areas of concern to the shipbuilder. One concern is that of accuracy control and quality improvement for building an assembly to specification. The other is that of unit fit-up during the erection process to minimize rework.

The accuracy requirements (tolerances) for the various parts embodied in the aft erection butt of an assembled block were:

1. Shell plate panel: Length +/- l/8 in. and Chord +/- 1/8 in;
2. Longitudinal and shell stringer placement on the deck, longitudinal bulkhead and side shell: +/- 118 in;
3. Transverse bulkhead on bulkhead/deck sub assembly: +/- 3/16 in; and
4. Final assembly: +/- 1/4 in.

Computer Linked Digital Theodolite

The specific system tested was Kern Instruments Inc.'s "Electronic Coordinate Determination System" (ECDS-2). Kern has been bought by another company and the ECDS-2 is no longer marketed in this country, but similar systems are available. The object of the test was to check the positions of longitudinals, shell stringers, decks and bulkheads of the aft erection butt of a completely assembled bilge block. Figure 1 shows an isometric of the erection butt and the targeted points.

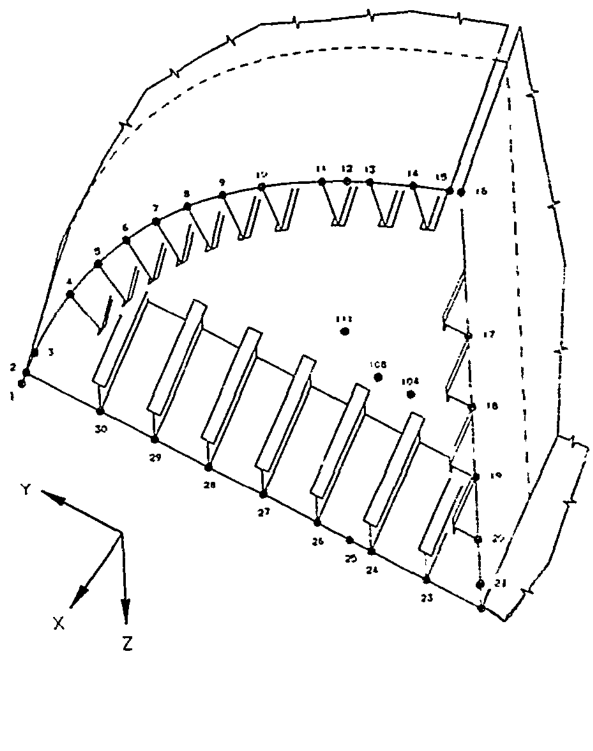

FIGURE 1

ERECTION BUTT AND TARGETS

In planning a theodolite set-up, it is necessary to determine whether a local or object coordinate system will be used. A local system produces offset data with the origin of the coordinate system at one of the theodolites. An object system produces offset data relative to the ships coordinate system. However, to use the object system, three known points (control points) are required by the computer software to set up a coordinate system. In this test the object system was used.

The control points can be obtained in a number of ways. If three points on the object are known precisely i.e., from the ship's offset file, the impact of the mathematical best-fit algorithm and, therefore, the residual error applied to the individual measurements, is minimized. Since there is already some question as to the built dimensions of the object, the ideal method is to locate the control points off the object of interest. However, this is difficult to achieve because each theodolite must "see" the control points. Measurement geometry restrictions associated with placement of theodolites does not facilitate the use of off object control points.

A second method to obtain the control points is to measure three or four points in a local system and, using the transformation software module, translate and rotate each point from a local system into an object system.

For this field test, two control points on the erection butt and one on the transverse bulkhead (required for depth), taken from the ship's offset file, were used. When using either a local or object coordinate system, it is necessary to input the x, y, and z coordinates of the control points into a control file. The software accesses this file when setting up the coordinate system.

The coordinate system must be oriented properly to avoid anomalous output. In this case, the block was upside down with the z-axis rotated downward.

Theodolite placement at the site requires clear sight lines to each target. An angle of 60 to 120 (maximum) degrees between the lines of sight from the theodolites to each target should be maintained to achieve acceptable accuracy. Outside these limits, accuracy decreases markedly. Figure 2 shows a typical measurement geometry. For this field test, adequate space was available to maintain an acceptable angle between the lines of sight and yet still be able to measure the complete erection butt without repositioning the theodolites. However, there are many areas within a shipyard where space is limited, i.e., in assembly, outfitting, storage, etc., which makes measuring the object more difficult and, therefore, increases costs.

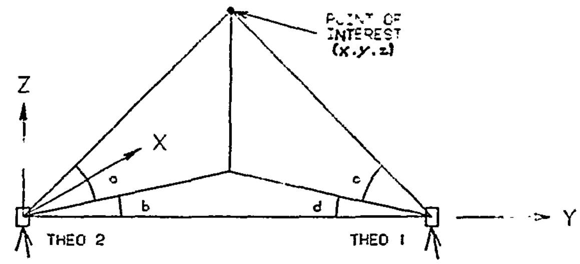

FIGURE 2

THEODOLITE MEASUREMENT GEOMETRY

A number of operating restrictions that affect accuracy must be considered when planning a measurement job. These are:

1. Thermal expansion of the object if exposed to direct sunlight;
2. Ground compression from gantry cranes, mobile cranes, heavy forklifts and trucks in the immediate vicinity of the theodolites;
3. Stability of surfaces on which the theodolites are set; and
4. Thermal expansion of the theodolite in direct sunlight.

Individual discrete points of interest on the object must be highlighted with some type of target. For this evaluation, 1" by 1" adhesive backed, aluminum foil cross haired targets were used. For this field test, which required targets on the edge of shell plates, etc., standard targets proved cumbersome. A better solution was to use a small punch mark (approximately l/16 in. diameter) filled with a drop of yellow paint. In all, the erection butt required 33 targets and placement was such that each was visible from both theodolite positions. Points of interest that were targeted (Figure 1) included the positions of deck and bulkhead longitudinals, shell stringers, sight edges, and a transverse bulkhead. A lift was required to place many of the targets.

The on-site operating procedure included placement of the targets, equipment set-up, removal of sight-line interferences, and the measurement. Equipment assembly and disassembly consisted of setting up and positioning two tripods, attaching theodolites to the tripods, leveling tripods and theodolites and connecting cables between the theodolites, power box and the computer.

Orientation of the coordinate system was done by pointing the theodolites in the directions of the X and Y axes and at each other. The distance to one control point from both theodolites was measured with a tape measure. Then the three control points and the scale bar were sighted-in and the bundle adjustment made.

The "bundle adjustment" is the mathematical triangulation process the computer uses to set up the coordinate system. Computer process time may be 1 to 2 minutes and may not be successful if there has been an operator error in sighting in the control points, recording the control points, or the control point coordinates are incorrect as entered into the control file. The accuracy of the coordinate system is reported in terms of Root Mean Square (RMS) (in, ft, or m) and indicates the amount of error that is to be applied to each individual measurement to be taken in the "On-Line" mode.

After the coordinate system has been created in the bundle adjustment, it is a relatively simple but tedious matter to manually sight-in the points of interest in the "On-Line" operating mode. Each operator sighted-in on the target, the RMS error was checked for acceptability, and the point was recorded. The coordinates of each point of interest are displayed instantly on the screen and stored to a file. The time necessary for sight-in is approximately 1 minute per point.

The output offset data analysis is performed to build confidence in the system's ability to deliver accurate data (in the form of offsets) for the process tested and to check the usefulness of the output. The accuracy achieved by the ECDS-2 system is reported in two parts.

Part one is the accuracy (error) of the bundle adjustment which is reported terms of a Total Root Mean Square (RMS). For this bundle adjustment the RMS error was 0.0002 ft. The Total RMS error is applied to each point of interest recorded in the "On-Line" mode as a correction factor. The second part of the accuracy reporting is the RMS error associated with each individual point of interest measurement in the "On-Line" mode and indicates the amount of error for each measurement.

The process accuracy- was tested by comparing machine produced point to point measurements (using the "Distances Function" of the "Special Functions" module) and comparing them to three manually measured (via tape measure) point to point measurements. In both cases, the system reported accuracy and the' accuracy from the point to point accuracy comparison were found to be well within the required process accuracy.

The usefulness of software produced output was tested by a comparison of the design offset file to the machine produced offset file. The software makes provisions to compare one measurement offset job file to another. However, no provision has been made to compare a Kern produced offset file to a ships offset file. This leads to a tedious and time consuming manual comparison to determine the difference between the nominal (design) values and the theodolite measured values. End usefulness is enhanced by the conversion module which converts decimal feet to feet, inches, and fractions.

This particular field test is representative of any large 3-D measurement job, i.e., blocks, large subassemblies, etc.; consequently, time required to target and measure smaller subassemblies and fabricated parts will be considerably less.

Man-hours and time required to complete one measurement job is a function of the number of targets to be placed, the difficultly placing them, and the number of points to be measured. Generally, the man-hours and time required for planning, assembly and disassembly, orientation, bundle adjustment, and data analysis are fixed.

The Digital, computer linked theodolite is a relatively low cost, accurate instrument applicable to almost any shipbuilding process. However, it is not without its shortcomings. Advantages and disadvantages are listed in Table II. A relatively simple measurement job takes nearly 7.25 man-hours. With careful scheduling, coordination and a well trained and experienced two person crew, efficiency may be increased to complete two measurement jobs of this type per 8 hour shift. The many shortcomings of this system do not recommend it for applications where large numbers of measurement jobs in many different locations are required.

The AIMS 2 (Analytical Industrial Measuring System) (5) and the CAT 2000 (Coordinate Analyzing Theodolite) (6) system are systems very similar to the ECDS2.

Convergent Photogrammetry. Automated Analysis

Photogrammetry is the science of acquiring and interpreting 3-dimensional data of physical objects by recording, measuring and analyzing photographs. The system field tested was Geodetic Services, Inc.'s "Simultaneous Triangulation and Resection System" (STARS) (3).

Data acquisition is performed by the photogrammetric camera, utilizing retroreflective targets highlighted by a strobe light to assure instantaneous target definition and produce photos with 2-dimensional x-y coordinates. With more than two exposures of the object from different locations, multiple horizontal and vertical angles describe each point of interest (Figure 3). 'Accuracy errors are minimized through redundancy. The actual 3-dimensional positions of the points of interest are calculated off-site.

ADVANTAGES

1. Relatively low capital cost.
2. Accuracy adequate for shipbuilding tolerances.
3. Applicability to many processes.
4. Real time results.
5. Rugged and reliable.
6 Software menu driven.

DISADVANTAGES

1. Due to time required to target, set-up and take-down equipment and operate, the system is inefficient and costly to operate for timely completion of large numbers of measurement jobs.
2. Experience with the system is necessary to use the system effectively.
3. Extreme angles between theodolites and between the theodolites and the targets must be avoided.
4. A stable platform is required for the theodolites.
5. Theodolites are unable to “see” targets if object of interest is back)lighted by the sun or if the sun’s rays shine directly into the lens.
6. If the job has a large quantity of points to be measured, the operators may become susceptible to theodolite sight)in and computer input error through fatigue.
7. Targeting is required.
8. Illumination of object necessary for low light measurement jobs.
9. Measurement on large objects in tight spaces is difficult, i.e., two blocks positioned close together in an assembly, storage area, etc.
10. A minimum crew of two persons required for efficient operation.
11. Motorized transportation for the system is desirable due to its bulkiness.

TABLE II

ECDS2 SUMMARY EVALUATION

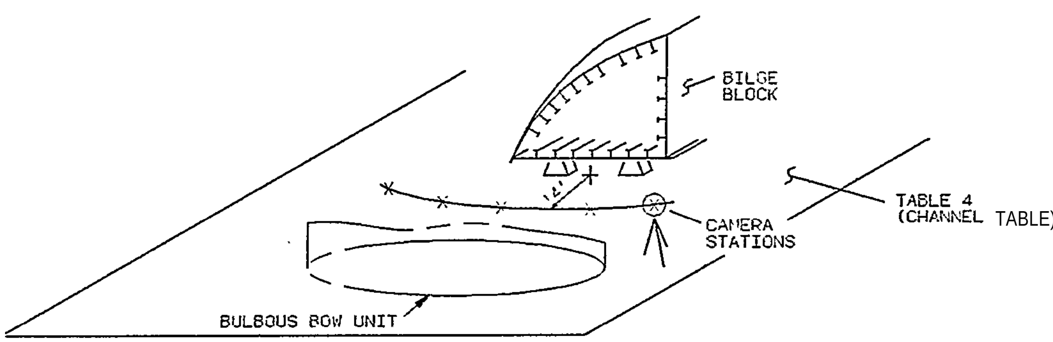

FIGURE 3

STARS CAMERA STATIONS

The photogrammetric camera is of "medium" format (4 l/2 in. by 4 l/2 in.) and, as opposed to glass plate types of cameras, it is a microprocessor controlled and monitored roll film camera. This camera minimizes the inherent errors introduced when using roll film through vacuum stabilization and internal calibration marks.

Two dimensional coordinates are extracted from the negatives by the AutoSet monocomparitor which is automated and computer driven ,requiring very little human intervention or skill to operate. The bundle adjustment used is a best-fit algorithm based on the familiar mathematical model originally developed for photogrammetry and runs on a personal computer.

Accuracies of 1:250,000 of the size of the object are achievable, depending on the number of photographs taken and the positions of the camera stations.

Photogrammetric network modeling and optimization is accomplished through a Computer Aided Design (CAD) based, interactive "Photogrammetric Simulation Program" (SIM) supplied with the STARS Standard Software Package. The photogrammetric simulation program minimizes on-site time and optimizes accuracy for the available space by predicting the number and position of camera stations, camera aim points and the number of photos per station required for complete coverage.

The on-site operating procedure included target placement, set-up and take-down of equipment and measurement job execution.

Special targets must be placed at all points of interest. The targets are adhesive backed, 5/16 inch diameter, and retroreflective. Equipment assembly and disassembly was a simple matter of attaching and detaching the camera to the tripod (the camera can also be hand held), positioning the scale bar and moving the camera to each of the five predetermined stations.

The execution of the measurement job, which took place in the rain and without interruption of on-going production work, required 20 minutes. Fourteen photographs were taken from five different positions on an approximately 14 ft. arc radius from the object (Figure 3).

Data Analysis

After the development of the photos, extraction of the point of interest x-y coordinates from seven of the fourteen photographs was accomplished with the AutoSet monocomparitor and accompanying software. The operating procedure consisted of:

1. Mounting the first negative on the digitizer pad and a duplicate negative on the AutoSet;
2. Entering some start up information;
3. Manually digitizing one fiducial (internal control reference point) and one reseau (internal film calibration points). The AutoSet automatically drives to and measures the remaining three fiducials and 24 reseaus; and
4. Manually digitizing three to six targets.

The AutoSet automatically drives to and measures the remaining targets by utilizing the original object offset file to calculate the approximate positions of the points of interest. As the AutoSet works, it may not be able to measure an occasional point. These targets are stored in a review file for the operator to attempt to manually digitize when the mensuration of that particular negative is completed.

After the first negative is finished, the process is repeated for the remaining six negatives. The final step is to execute the bundle adjustment which takes approximately l-2 minutes on a personal computer.

The procedure required 1 hour and 10 minutes to analyze seven negatives. If no prior information is known about the points of interest (i.e. no offsets available), the procedure requires approximately l/2 hour more time to establish approximations to allow the AutoSet to automatically drive to and measure the targets.

Upon completion of the bundle adjustment, accuracy indices are produced by AutoSet as standard deviations in each of the the x, y and z directions which, unlike the theodolite bundle adjustment, processes and calculates the x y, and z coordinates of each point of interest in one batch. The standard deviations for this field test were x = 0.13mm (0.005 in), y = 0.08mm (0.003 in), and Z = 0.08mm (0.003 in). These deviations are applied to each individual measurement as an error correction factor. The ability of the system to meet the process accuracy was tested by comparing the STARS produced point to point measurements with those produced manually by tape measure. As indicated by the bundle adjustment standard deviations and the point to point comparison, the system is capable of accuracies well above those required in the shipbuilding environment. The accuracy produced is proportional to the square of the number of photographs taken of a point of interest at each station. To achieve shipbuilding accuracies a minimum of two photographs are needed.

The convergent photogrammetry system evaluated, STARS, is an accurate and flexible measurement system, well suited to the varied applications and environmental conditions found in shipyards. Advantages and disadvantages are shown in Table III. Integration into the total production process is enhanced by the system's off-site planning capabilities and minimized on-site time for the efficient inspection of a large number of objects. Conversely, use of the STARS system as an on-site building tool is handicapped by the short but distinct delay for results feedback.

Similar systems are available from Wild Heerbrug and John F. Kenefick Photogrammetric Consultant, Inc.(Wild/JFK Industrial Photogrammetry System) and from Rollei Fototechnic GmbH & Co KG, Instrument Division (Rollei Fototechnic Photogrammetry System).

ADVANTAGES

1. It is applicable to many production processes.
2. It is flexible and able to overcome adverse environmental or varied measurement geometry conditions;
3. The camera is rugged, reliable, and designed for ease of maintenance;
4. The monocomparitor is highly automated and the number of points of interest that can be measured is essentially unlimited;
5. Accurate to shipbuilding processes .
6. Requires only one person for planning, on-site execution, and off-site data reduction.
7. High skill level not necessary
8. Efficient for large quantities of measurement jobs where real-time results are not necessary,
9. Data acquisition is highly redundant for consistent results.
10. No illumination of object required.
11. No control points required to set up the coordinate system.

DISADVANTAGES

1. High capital cost
2. Targeting required.
3. Results turn around is not real time and is dependent on the number of points of interest.

TABLE III

STARS SUMMARY EVALUATION

Optical Laser

The optical laser based coordinate measuring device is a hybrid, a combination theodolite and laser that uses the common navigational principle of bearing and range in a predetermined 3-dimensional coordinate system to locate a point in space. The angles (bearings), between the line of sight from the measuring device to the target and the x and y axes of the coordinate system, are determined by the optics (much like a theodolite). Distances (range) to the targets are measured by a laser. The system uses dedicated hardware to perform calculations (as opposed to software) on the horizontal and vertical angles and the distance to calculate the x, y and z coordinates of the point of interest (Figure 4). The system is similar in some respects to the operation of digital theodolites, but is freed from many of the measurement geometry restrictions inherent in theodolite systems by using only one measuring device.

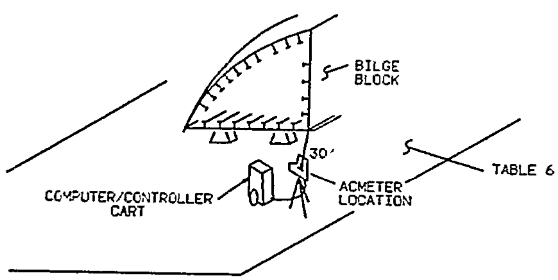

FIGURE 4.

ACMAN MEASUREMENT GEOMETRY

The system field tested was Prometrics Oy's "Manufacturing Accuracy Measurement and Control System" (ACMAN) (8). The total system has been developed, specifically to measure and support the construction and process improvement of hull block sub-assembly, assembly and erection. The system consists of 3 parts: the coordinate measuring device (ACMETER), a relational database for data storage and statistical process control (ACBASE), and a graphics package (ACCAD) for modeling shapes. The ACBASE and ACCAD software systems are designed to be interfaced (in terms of downloading files) with a yard's database and CAD systems to provide real time, on-site comparisons of the measured points of interest from their design values. Also provided are graphics routines to represent the object and automatic statistical process control chart graphing for process improvement. The software can also be customized and tailored to a yard's individual needs by the manufacturer.

The ACMAN system is capable of measuring points of interest in either local or object (block) coordinate system. The block coordinate system was used in this field test. Control points are used to establish the orientation of the block and object coordinate systems. The ACMAN system does not use an iterative mathematical best fit solution (i.e., the bundle adjustment) to ensure the accuracy of the points of interest measured. Three precisely known points are required for system orientation. It is necessary to know the precise coordinates of the control points because the accuracy of the measured points of interest is directly proportional to the accuracy of the control points. This is different from theodolites, which are able to calculate an acceptable coordinate system (with some error) even though the three control points may not be in the exact positions entered into the control file.

Three control points must lie on a plane and are used to establish the x, y plane. Two of these three control points are used to define the direction of the x-axis. The z-axis is automatically set 90 degrees to the x-axis for a right handed coordinate system.

Theoretically, and in practical application, it is best that these three control points not lie on the object being measured since there is already some question as to the dimensions of the assembly. This is especially so with the ACMETER due to its one to one accuracy relationship between the control points and the points of interest to be measured. Determining these three off-object control points was not practical for this field test; however, with an in-yard capability, this is a desirable and practical method to use and is facilitated by the one measurement station requirement.

The ACMETER (with its tripod) must be placed such that all control points and points of interest are visible. With only one measurement device necessary, the placement of the ACMETER is very flexible and adaptable to the available space. In this field test, the ACMETER was placed off to one side of the block to demonstrate its placement flexibility. The z-axis of the block is downward and perpendicular to the ground.

The ACMETER is most effective at a distance from the object of between 3m (9.8 ft) and 30m (98 ft).

Individual discrete points of interest on the object must be highlighted with the manufacturer supplied adhesive backed, bulls- eyed targets. To optimize accuracy for this test, which required targets on the edge of plates, the targets were placed at an angle to the object so that the operator's line of sight remained perpendicular to the targets which. The erection butt required 29 targets.

Equipment assembly and disassembly consisted of wheeling the cart containing the ACMETER, lap top computer and laser power unit into position, setting up and positioning the tripod, attaching the ACMETER to the tripod and connecting cables between the measuring device, laser power source and the computer.

Actual measurement was a two step process Orientation of the coordinate system was first. In the local system, the 3 control points, which define the reference plane, were sighted in and entered. The system does an automatic transformation of the control points from a local to a block coordinate system.

After the coordinate system has been created it is a relatively simple but tedious matter to sight-in the points of interest. The coordinates of each measured point are instantly displayed on the screen and stored to a file. Time for point of interest sight-in is approximately 1 minute per point.

The ACMAN's systems capabilities for data manipulation and statistical process control were presented but could not actually be demonstrated. During the measurement process, a measurement form was generated on-site which presents the x, y, and z coordinates of each point. When the offset file of the whole object is down-loaded, the nominal (design) values and the difference between the nominal and measured values are also presented. Statistical process control is displayed in the form of histograms, X-bar and range chart is also available on-site.

The ACMAN system is a well thought out system, accurate to shipbuilding tolerances and applicable to many of the processes described in this report. 'Advantages and disadvantages of the system are shown in Table IV. Of the 3 systems field tested, ACMAN system strikes the best overall balance between flexibility, timely feedback, and acquisition cost. The system produces on-site real time results, with on-site operation ease approaching that of photogrammetry, and an increased measurement geometry flexibility over theodolites. It also presents many possibilities for total production process integration.

The ACMAN system seems particularly well suited to on-site building and inspection tasks during all phases of hull block construction. No similar systems are available.

ADVANTAGES

1. Developed for the shipbuilding industry.
2. Accurate to shipbuilding tolerances.
3. Applicable to many processes.
4. Rugged and reliable.
5. Integrated accuracy control and graphics.
6. Real time results.
7. Flexible; fewer measurement geometry restrictions.
8. One person operation.
9. On-site real-time feedback.
10. High skill level not necessary.
11. Results are absolute assuming control points precisely known.

DISADVANTAGES

1. High capital cost.
2. Stable platform required.
3. The ACMETER is unable to "see" targets if the object of interest is back lighted by the sun or if the sun's rays shine into the lens.
4. If the job has a large quantity of points to be measured, the operators may become susceptible to error through fatigue.
5. Targeting required.
6. Illumination of object necessary for low light measurement jobs.
7. Control points must be used to orient the block and object coordinate systems.

TABLE IV

ACMAN SUMMARY EVALUATION

CONCLUSIONS

Figure 5 is a generalized comparison of the three systems field tested. It shows a very clear inverse relationship of initial cost to the cost per measurement.

	Measurement System		
	Theodolites	Photo-grammetry	Optical Laser
Man-hours per Measurement	7.25	4.17	2.86
Cost per Measurement*	$ 362.50	$ 222.50	$143.00
Cost per System**	$65,000 .	$210,000	$182,200

* Based on average consultant labor rate of $50.00/hr.

• * Depends on options selected.

FIGURE 5

COST PER MEASUREMENT

Table V relates measurement tasks for the construction processes to the most appropriate measurement technique of those systems field tested. Each stage of construction is broken down into its constituent processes; furthermore, each process contains a number of measurement tasks that support "neat" hull block construction. The assigning of the numerical rank was subjective based on the evaluation of both qualitative and quantitative factors, There is no one system that has the capability to efficiently perform every measurement task. Therefore, this guide is suggested as a starting point for a, shipyard's investigation of its own needs for measurement techniques.

The most apparent aspect of the chart is that none of the measurement systems surveyed has the capability to conveniently and accurately measure both fabrication parts and large blocks. It seems that a complete measurement capability at a particular shipyard would use two or three complete types of systems, possibly with multiples of some of the less costly systems for measuring parts on an assembly line. It is also important to remember that nearly all the systems are under continuous development so that disadvantages described may be overcome by advances in the technology.

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6. Cubic Precision, K&E Electra Optical, 750 Huyler St., Teterboro, NJ.

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Legend

1–Good Efficiency
2–Fair Efficiency
3–Poor Efficiency
N/A–use mannual method

Stage of Construction		Processes		Measurement Techniques: Digital Theo–dolites	Photo grammetry	Optical Laser
Fabrication		Cutting Tees	Length, Prep of Cut, Degree of Bevel, Degree of Cut	N/A	N/A	N/A
		Stripping Plates	Width	N/A	N/A	N/A
		N/C Cut Plates	Length, Width, Diagonal	3	1	2
		Stripping I to Tees	Width of Stripped Flange	N/A	N/A	N/A
		Bending Tees	Chord, LOA, Sightline	3	1	2
		Bending Tees (Compound)	Chord, LOA, Sightline	3	1	2
		Bending Plates	Chord, Radius	N/A	N/A	N/A
		Twisting Tees	Angle from Vertical	3	1	2
		Rolling Plates	Length, Width, Curvature, Sight Line	3	1	2
Sub–Assembly		Paneling Plates	Length, Width, Diagonal	3	1	2
		Paneling Web Frames	Length, Width, Diagonal,	3	1	2
		Fitting Out Web Frames	Length, Width, Diagonal,	3	1	2
		Fitting Longs to Plate Edge	Relationship of Longs to Plate Edge	3	2	1
		Web Frames on Sub–Assembly	Declivity of Webs	3	2	1
		Web Frames to Plate Edge	Relationship of Webs to Plate Edge, Declivity of Webs	3	2	1
		Final Sub–Assembly Check	Length, Width, Diagonal	3	1	2
Assembly		Sub–Assembly Joined to a Sub–Assembly	Length, Width, Diagonal	3	2	1
		Setting Pins on Assembly Table	Heights	3	1	2
		Positioning Panels on Pins or Jigs	Position of Corners	3	2	1
		Panelling Curved Shell Grand Panel	Lengths, Chord, Diagonal	3	2	1
		Final Block Assembly Check	Length, Width, Diagonal, Key Hard Pts, Reference Lines	3	1	2
Erection		Pre–Erection:				
		Layout Ways/Graving Dock w/Buttock and Frame Reference Grid	Lengths, Widths	2	3	1
		Check Offset Dimensions of Key Hard Points on Transverse and Longitudinal Erection Butts of Block to be Erected and its Mating Block(s)	Deck & Bhd Longs, Girders, Sight Edges, Shell Stringers, Web Frames, Reference Lines	3	1	2
		Check Squareness of Frames to Reference Buttock Line of the Block to be Erected	Perpendicularity of Frames to the Buttock Reference Line	3	2	1
		Erection:				
		Set Block and Check Position of Reference Lines on the Block to Reference Lines on Ways	Offsets of the Block Reference Lines to Ways Reference Lines	2	3	1
		Check Positions of Key Hard Points on Tranverse and Longitudinal Erection Butts of Erected Block and Next Mating Block(s)	Deck & Bhd Longs, Girders, Sight Edges, Shell Stringers, Web Frames, Reference Lines	3	1	2
		Check Frame Spacing Between Blocks, Half Breadths and Heights to Maintain Overall Tolerances	Length Between Reference Frames, Half Breadths and Heights Above Baseline	2	3	1
		Check Height of Keel Blocks to Maintain Baseline	Height of Keel Blocks	3	2	1

TABLE V

CONSTRUCTION PROCESSES vs.MEASUREMENT TECHNIQUES

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